Finite-temperature equation of state and phase diagram from chiral effective field theory

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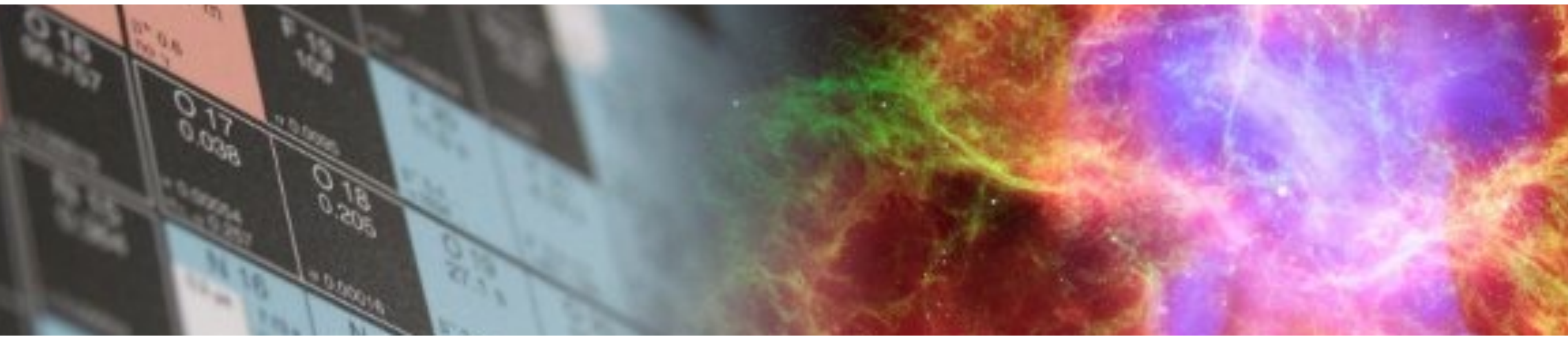
EMMI

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG



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Exzellente Forschung für Hessens Zukunft

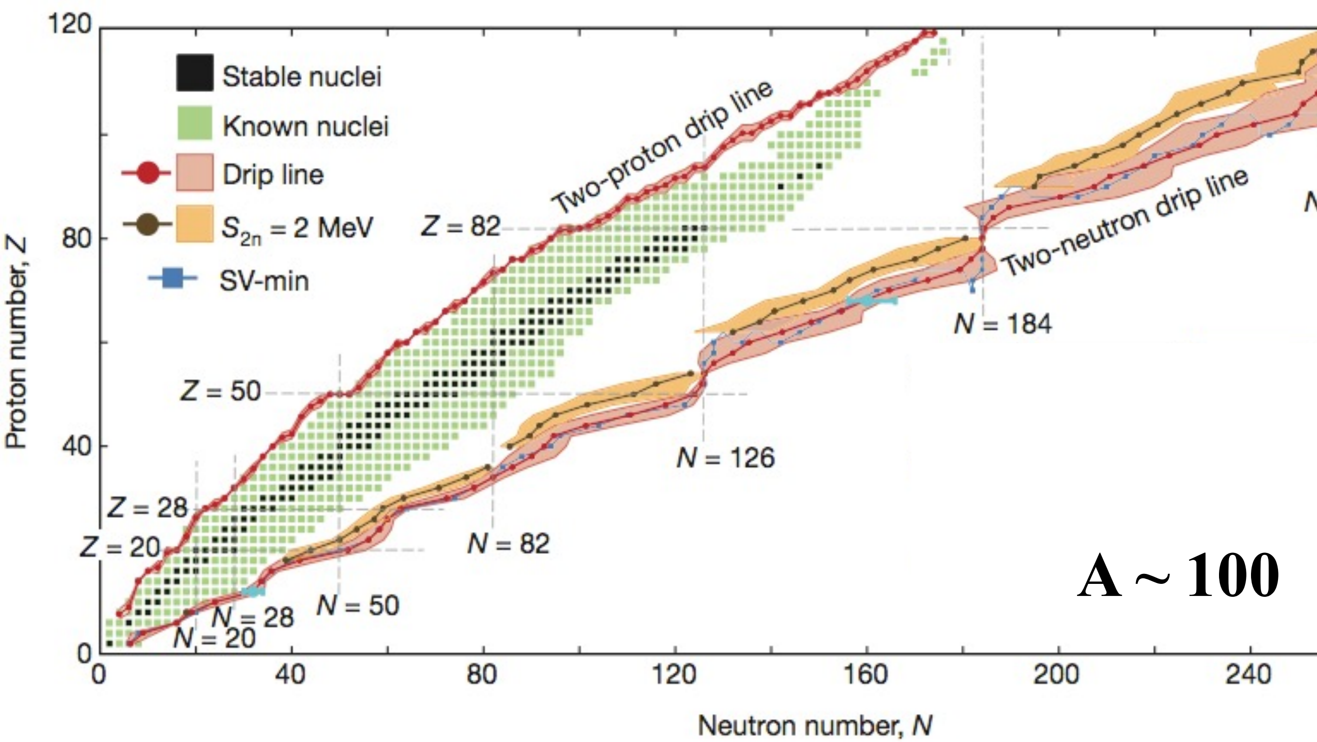
Structure of nuclei and dense matter in neutron stars

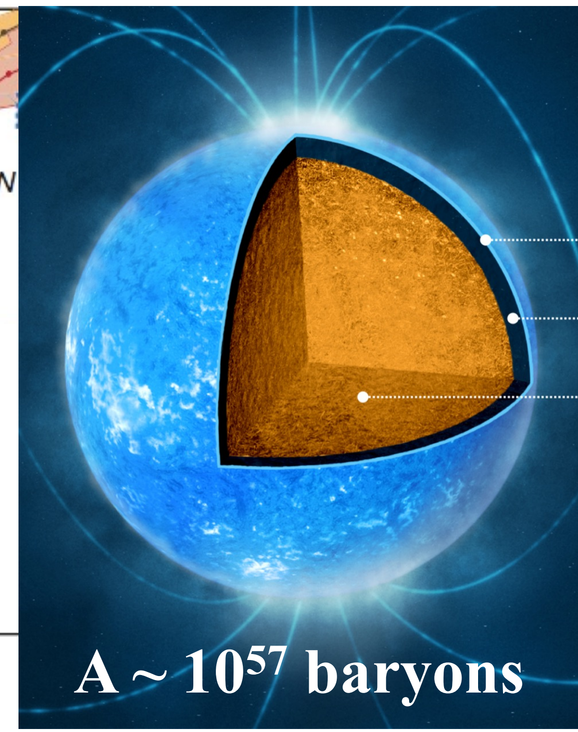
doi:10.1038/nature11188

The limits of the nuclear landscape

Jochen Erler[1,2], Noah Birge[1], Markus Kortelainen[1,2,3], Witold Nazarewicz[1,2,4], Erik Olsen[1,2], Alexander M. Perhac[1] & Mario Stoitsov[1,2]‡

~ 4000±500 nuclei unknown, extreme neutron-rich

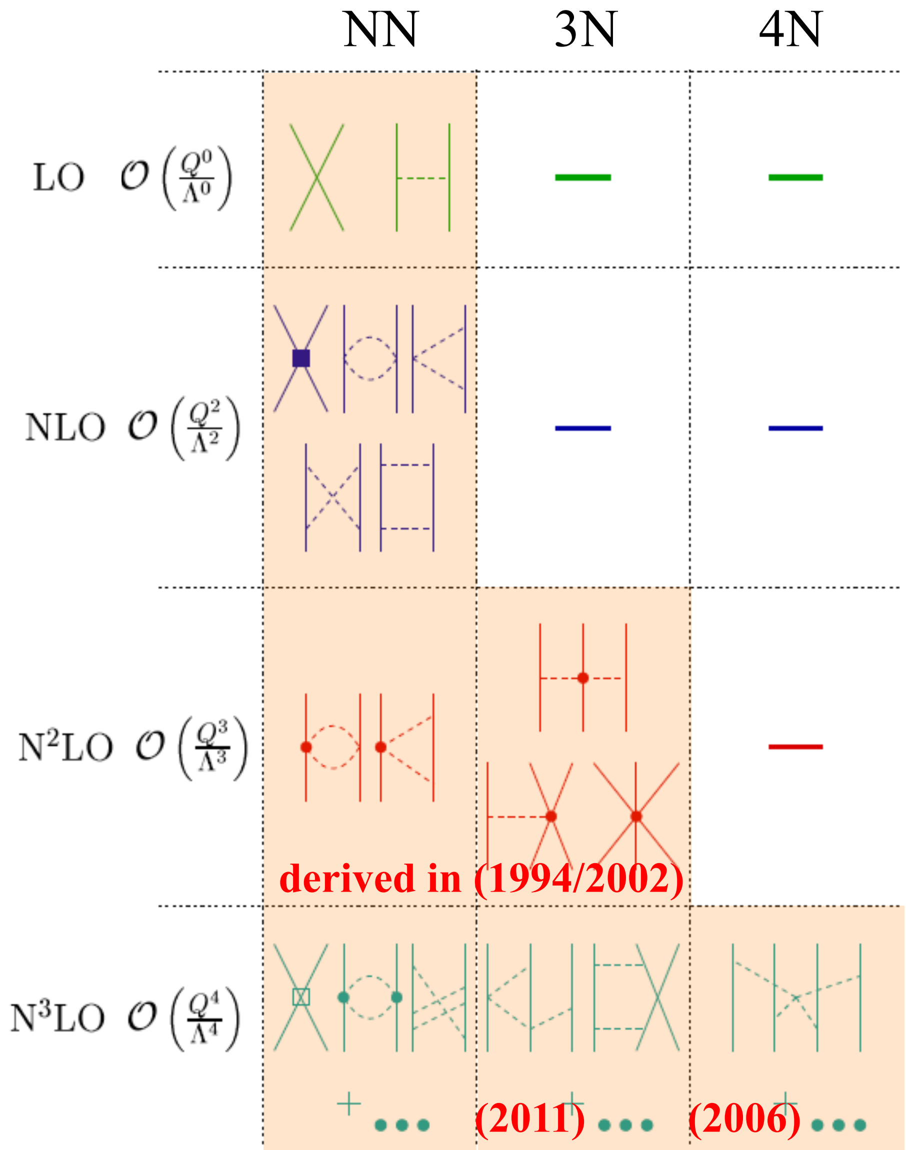


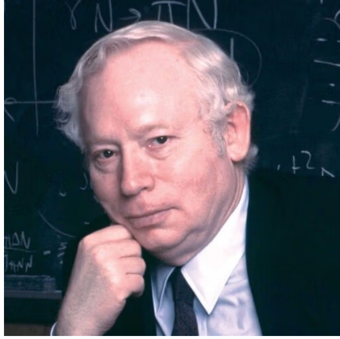


Extreme neutron-rich matter in neutron stars

Chiral effective field theory for nuclear forces

Systematic expansion in low momenta $(Q/\Lambda_b)^n$





based on symmetries of strong interaction (QCD)

long-range interactions governed by pion exchanges

powerful approach for many-body interactions

all 3- and 4-neutron forces predicted to N^3LO

Tews et al., PRL (2013)

enables uncertainty quantification from higher orders and input data

Weinberg (1990,91), van Kolck, Kaplan, Savage, Wise, Bernard, Epelbaum, Kaiser, Meißner,…

Great progress in ab initio calculations of nuclei

systematic interaction expansion + systematic many-body expansion

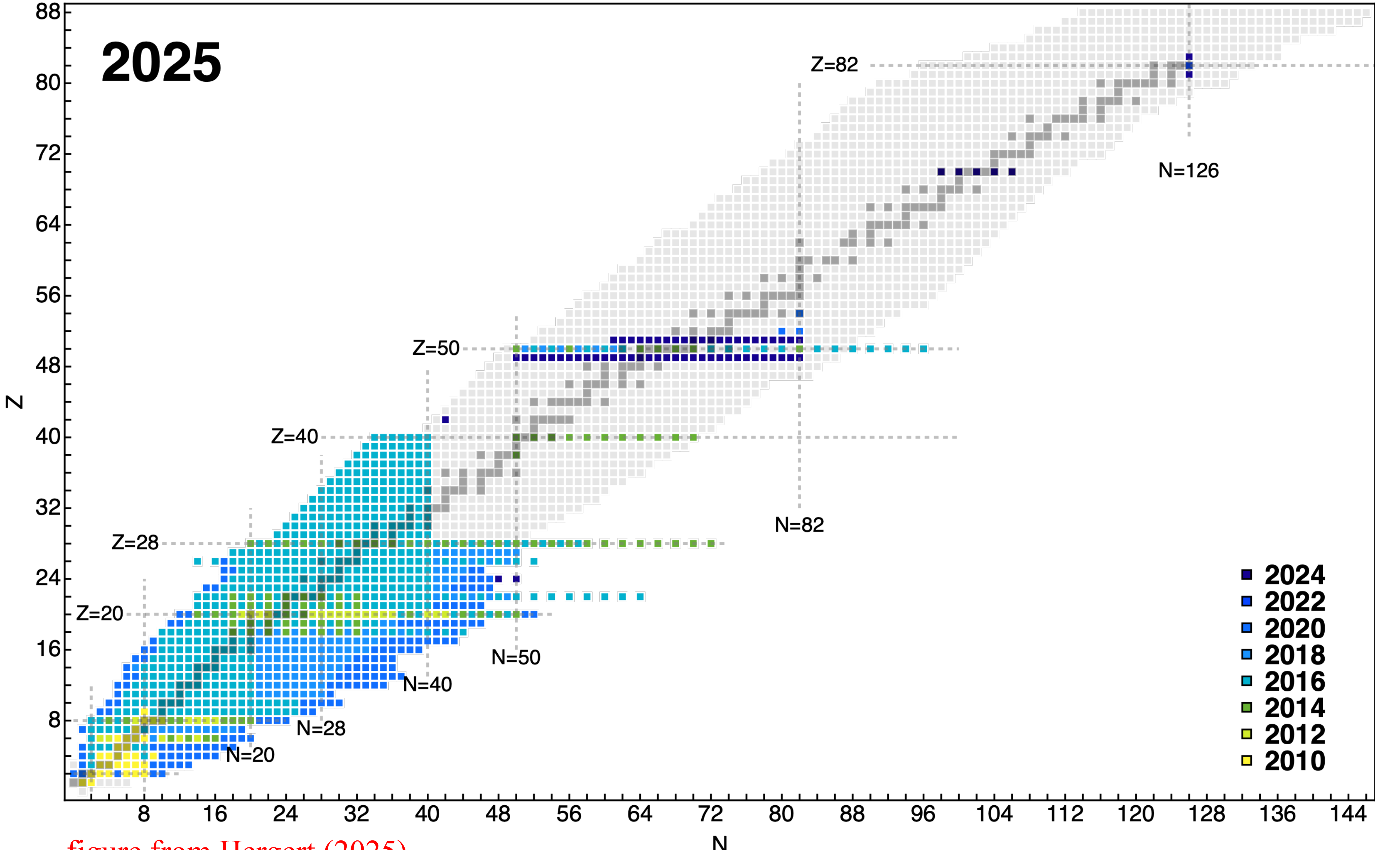


figure from Hergert (2025)

Nuclear masses around N=82 and r-process nucleosynthesis

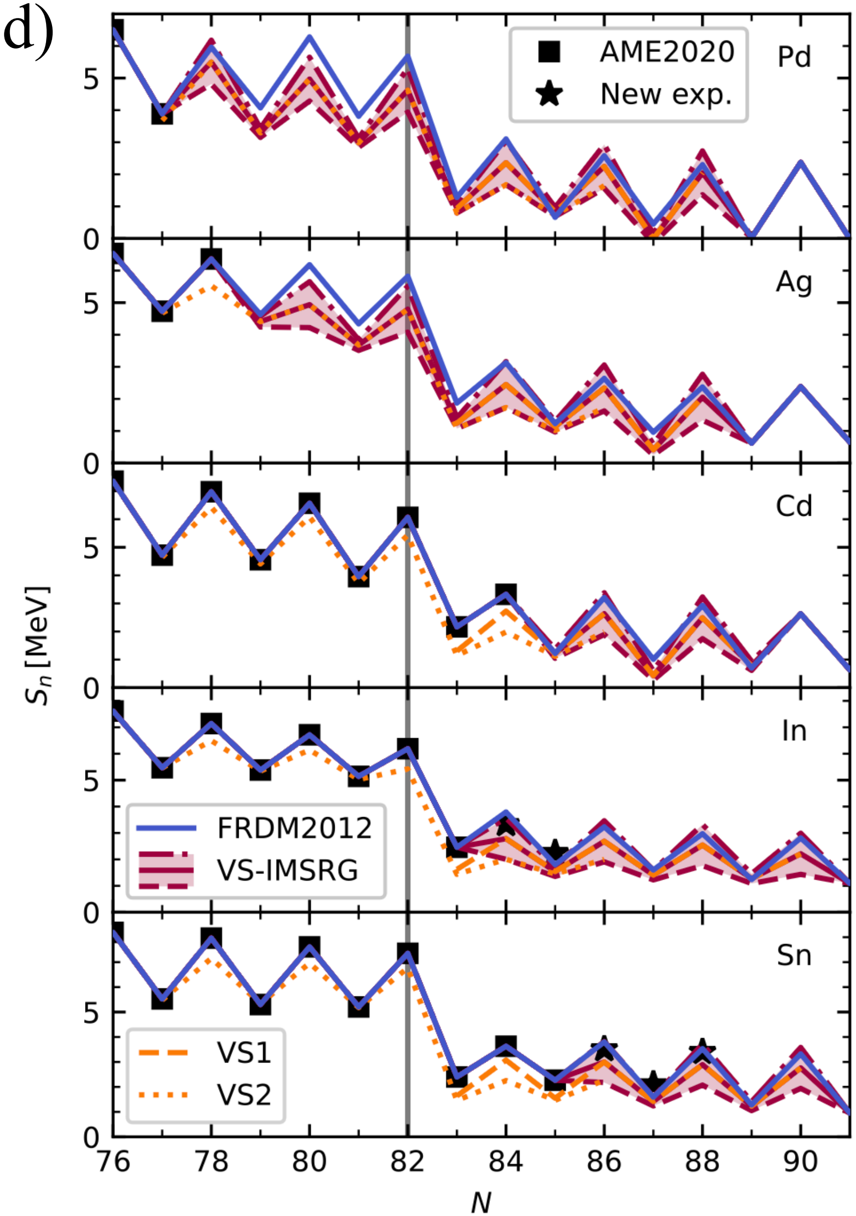
Kuske, Miyagi, Arcones, AS, arXiv:2509.19131

masses around N=82 (Sn, In, Cd, Ag, Pd)
→ interesting region at exp frontier

VS-IMSRG results with valence space
+ interaction uncertainties

separation energies have smaller uncertainties due to correlations;
IMSRG(3f2) is within VS1, VS2

incorporate VS-IMSRG masses
with uncertainties (min/central/max)
in baseline AME2020 + FRDM2012



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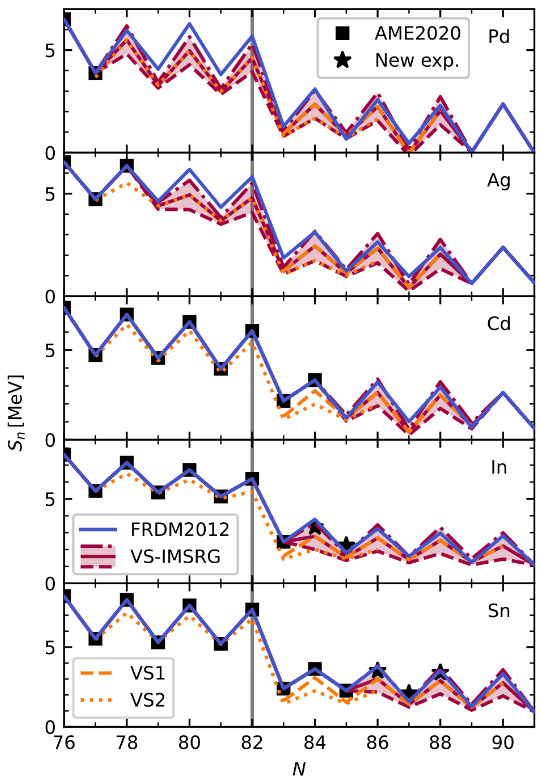
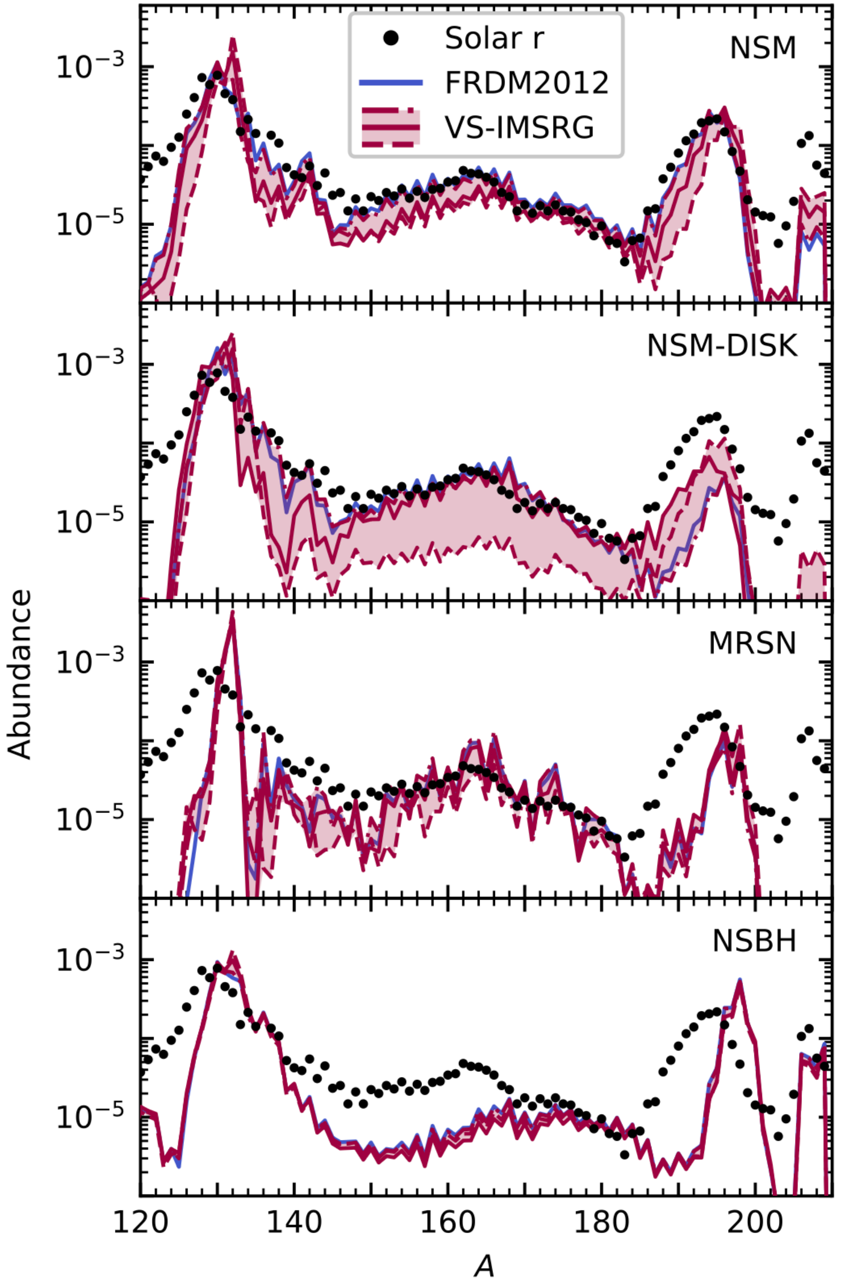
Kuske, Miyagi, Arcones, AS, arXiv:2509.19131

VS-IMSRG masses (min/central/max)

in baseline AME2020 + FRDM2012

explore r-process predictions for different astrophysics scenarios





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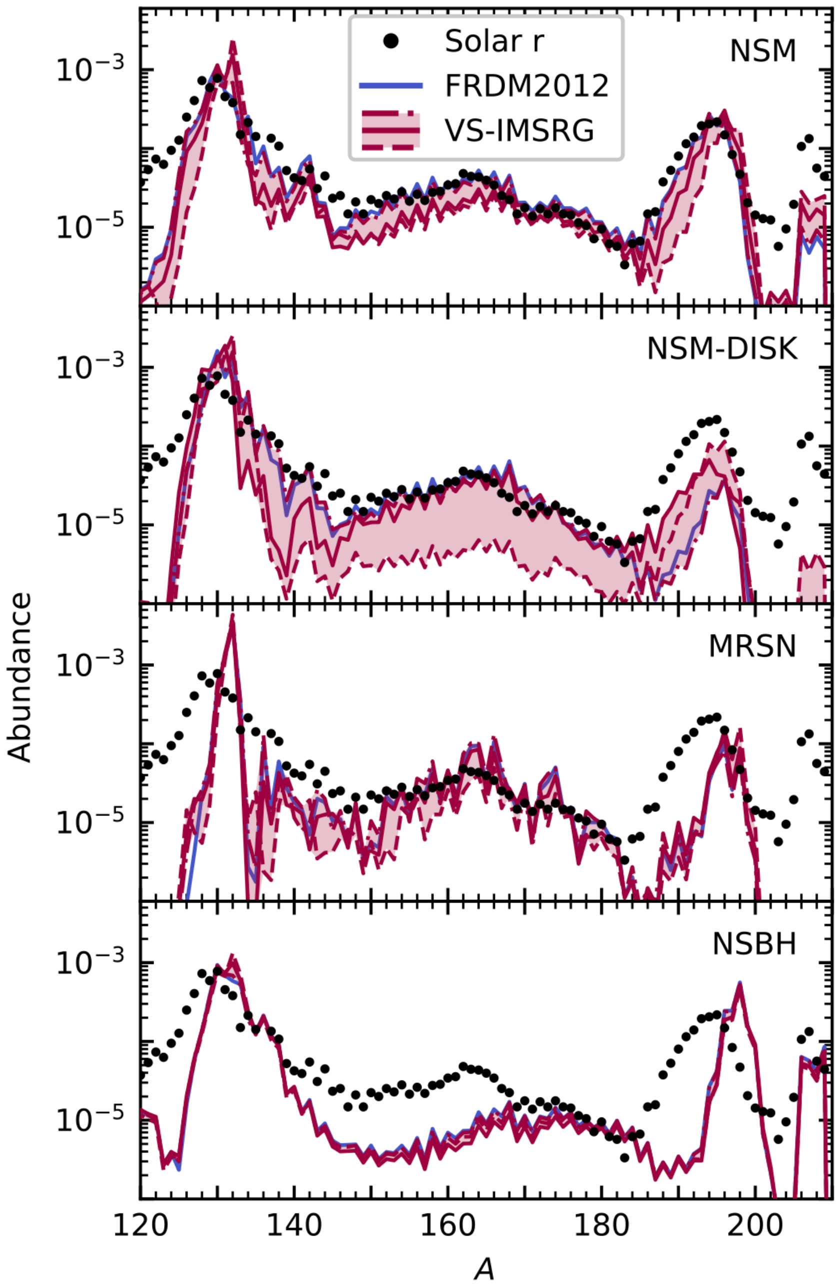
VS-IMSRG masses (min/central/max)

in baseline AME2020 + FRDM2012

explore r-process predictions for different astrophysics scenarios

largest effects for n-star mergers (NSM and NSM-DISK)

ab initio masses strengthen waiting point of 2nd peak, leading to slower nucleosynthesis flow, and important impact on 3rd peak

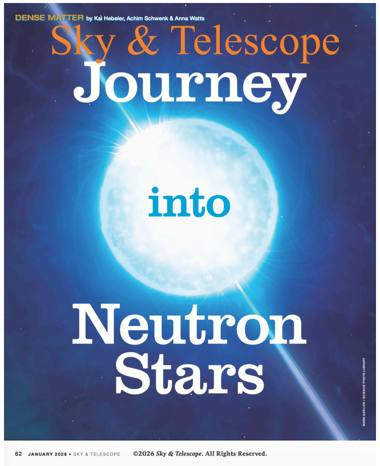


Extreme matter in neutron stars

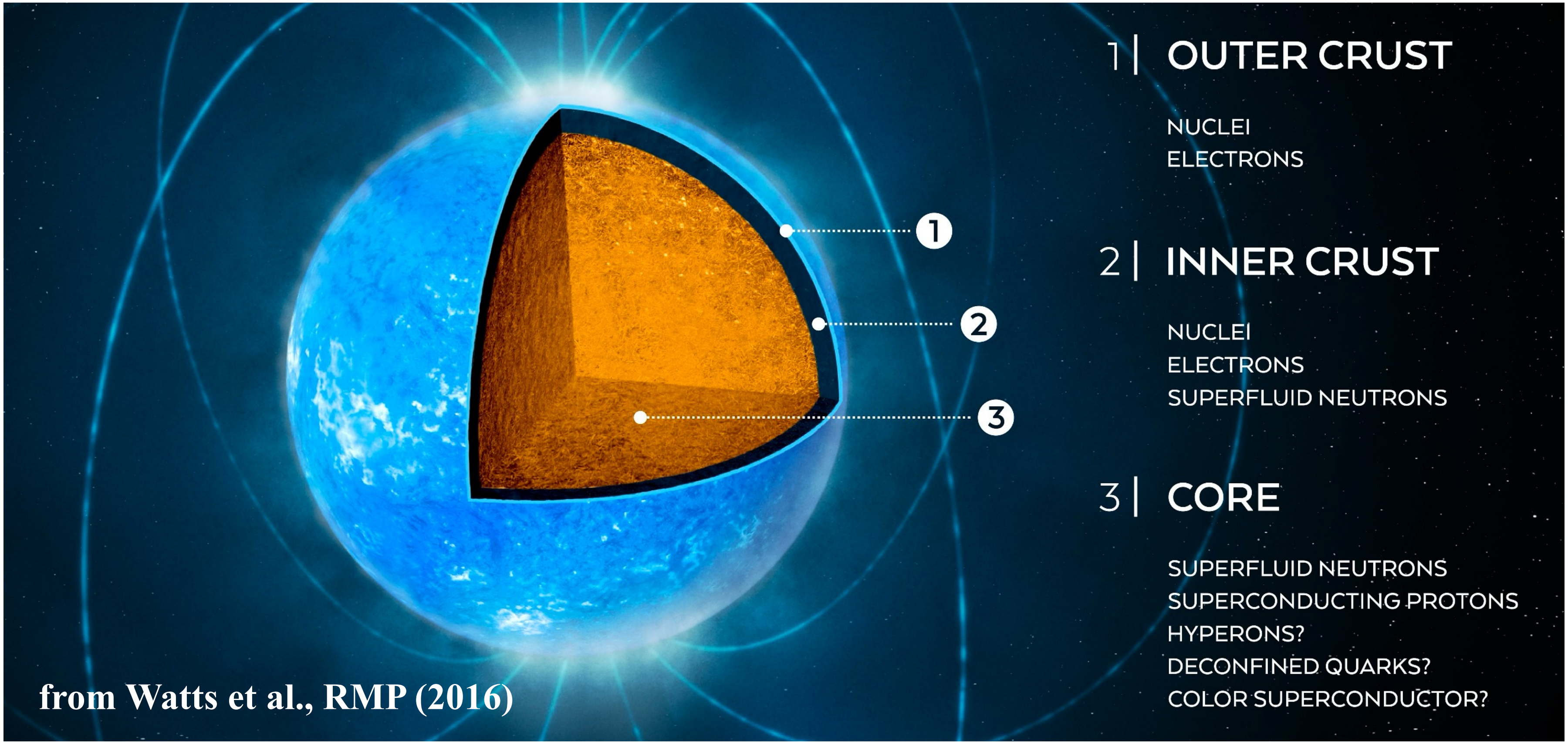
Dense matter up to ~3-8 n_0 (95% CI, in heaviest n stars)

governed by strong interactions, up to few n_0: n,p,e,μ

When (do) degrees of freedom change?



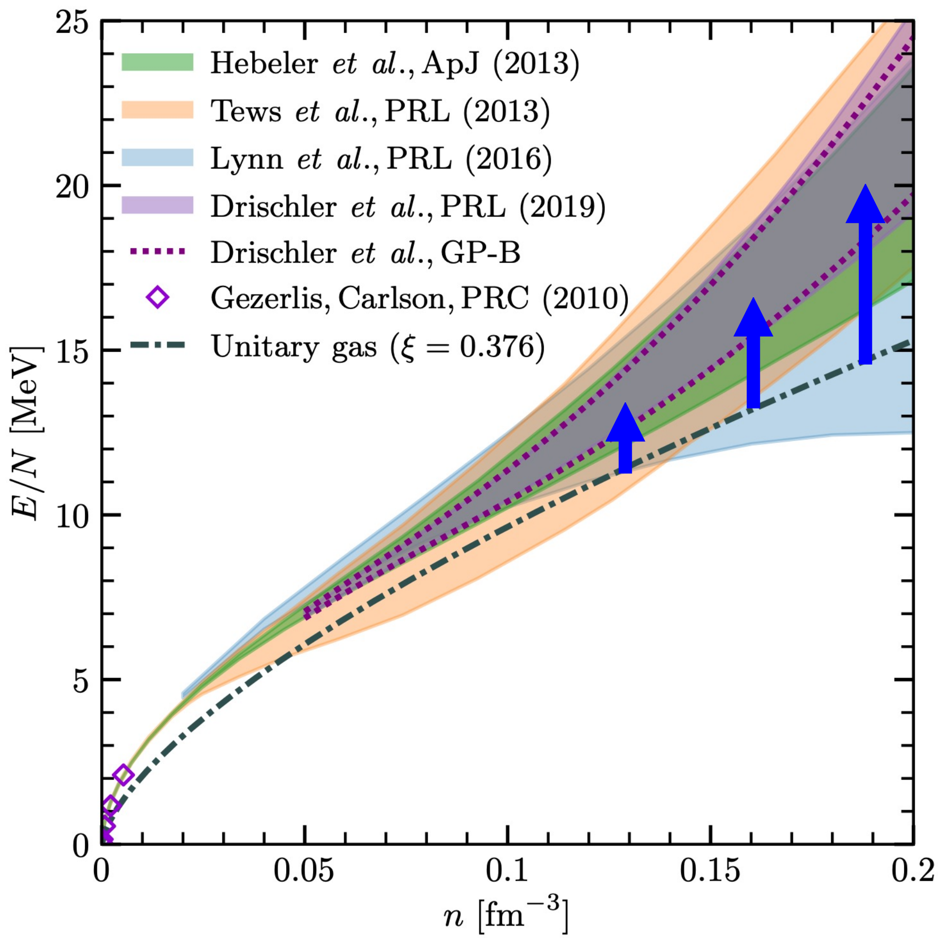
Chiral EFT sets pressure of first few km Hebeler et al., PRL (2010), ApJ (2013)



from Watts et al., RMP (2016)

Chiral EFT calculations of neutron matter

good agreement up to saturation density for neutron matter including NN, 3N, 4N interactions up to N^3LO



comparison from Huth et al., PRC (2021)

slope determines pressure of neutron matter

comparison to unitary Fermi gas measured with cold atoms

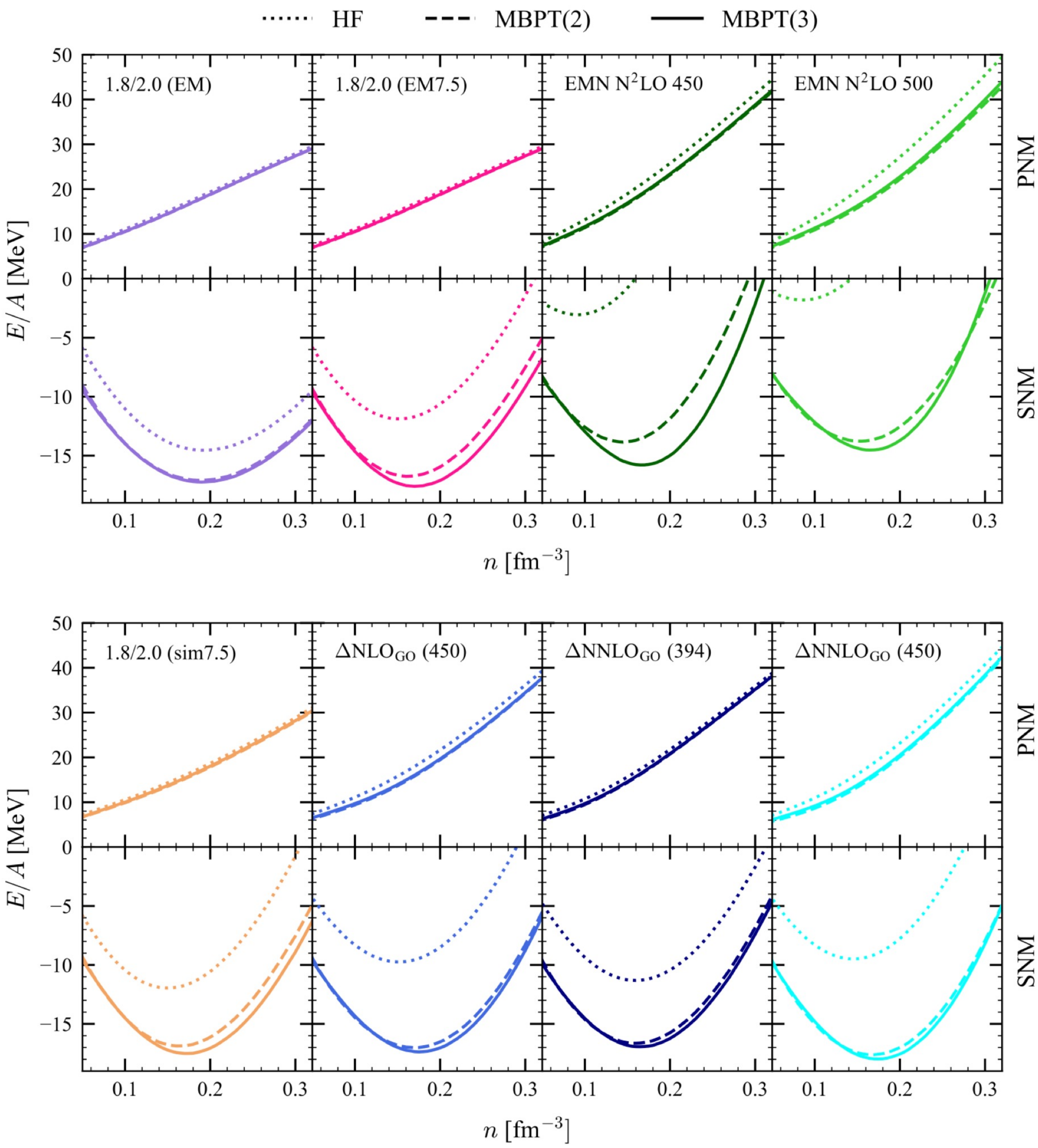
stronger increase towards higher densities (EOS becomes stiffer) due to repulsive 3N forces

Chiral EFT calculations of neutron matter

Alp, Dietz, Hebeler, AS, PRC (2025)

MBPT calculations with chiral NN+3N interactions used for ab initio calcs of medium-mass nuclei

very good many-body convergence, uncertainty dominated by interaction uncertainty (i.e., EFT truncation uncertainty)



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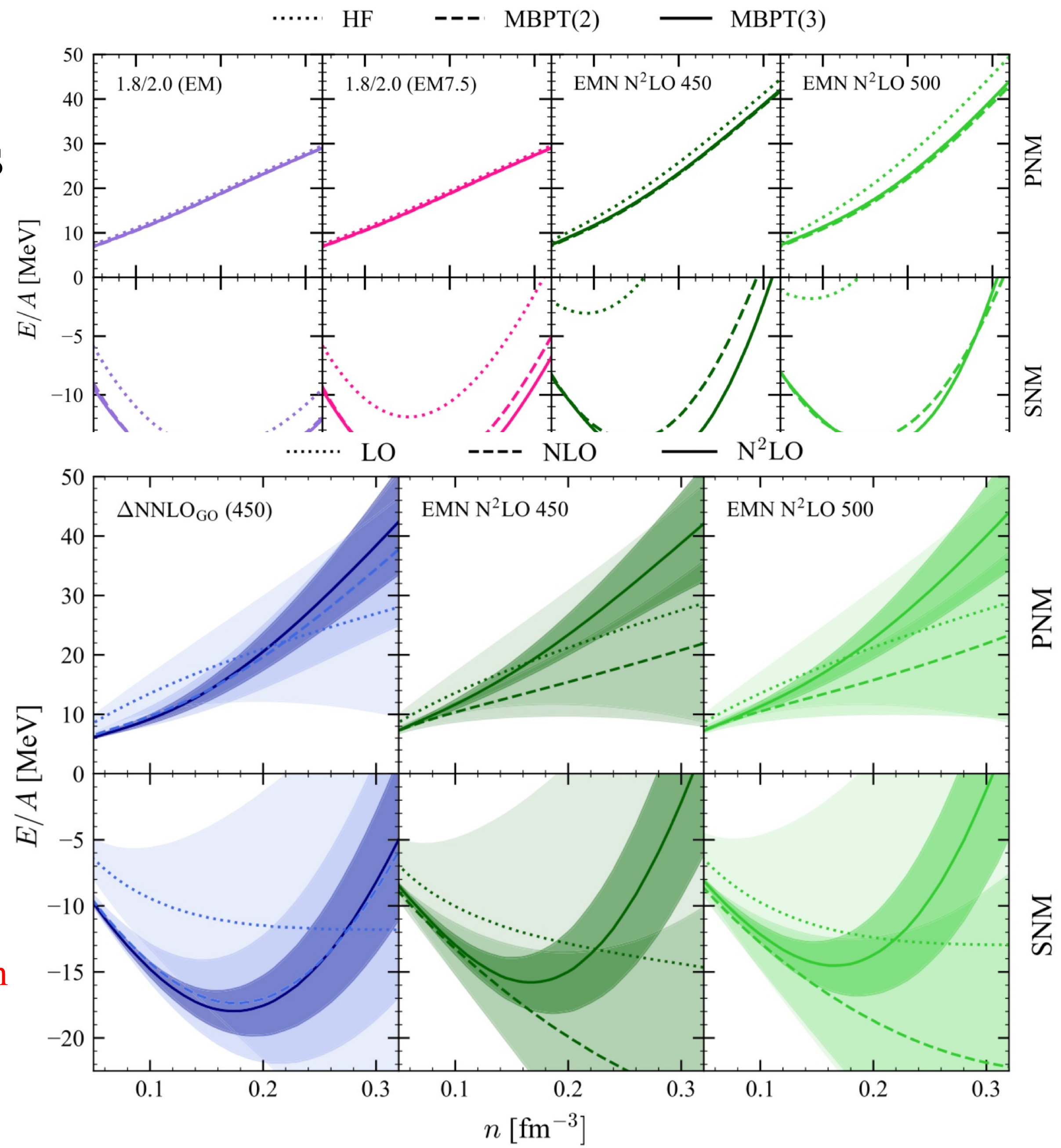
very similar results with Delta-full and Delta-less chiral EFT here with GP-Bayesian EFT uncertainties from H. Göttling



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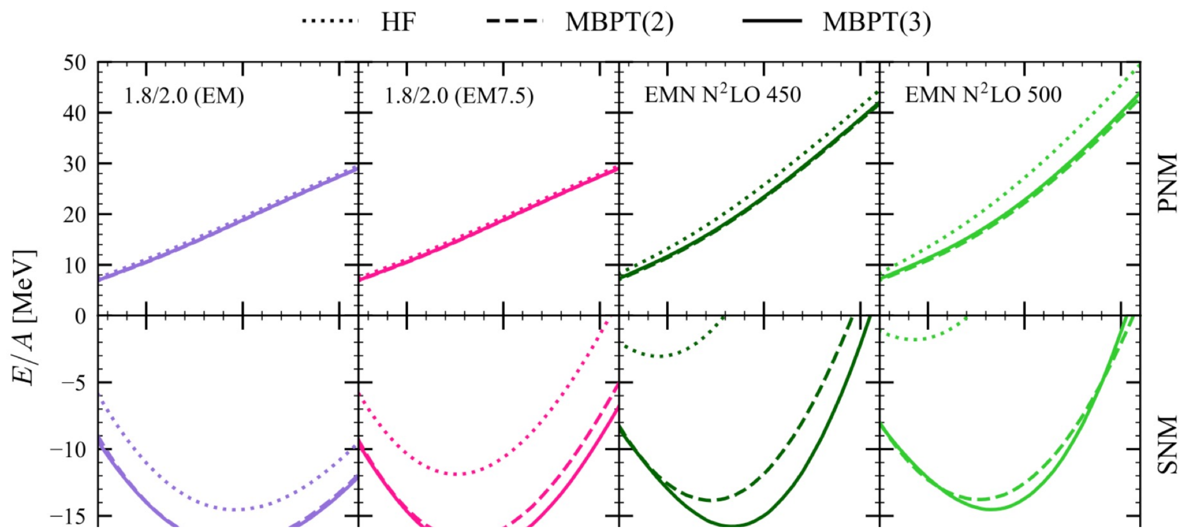

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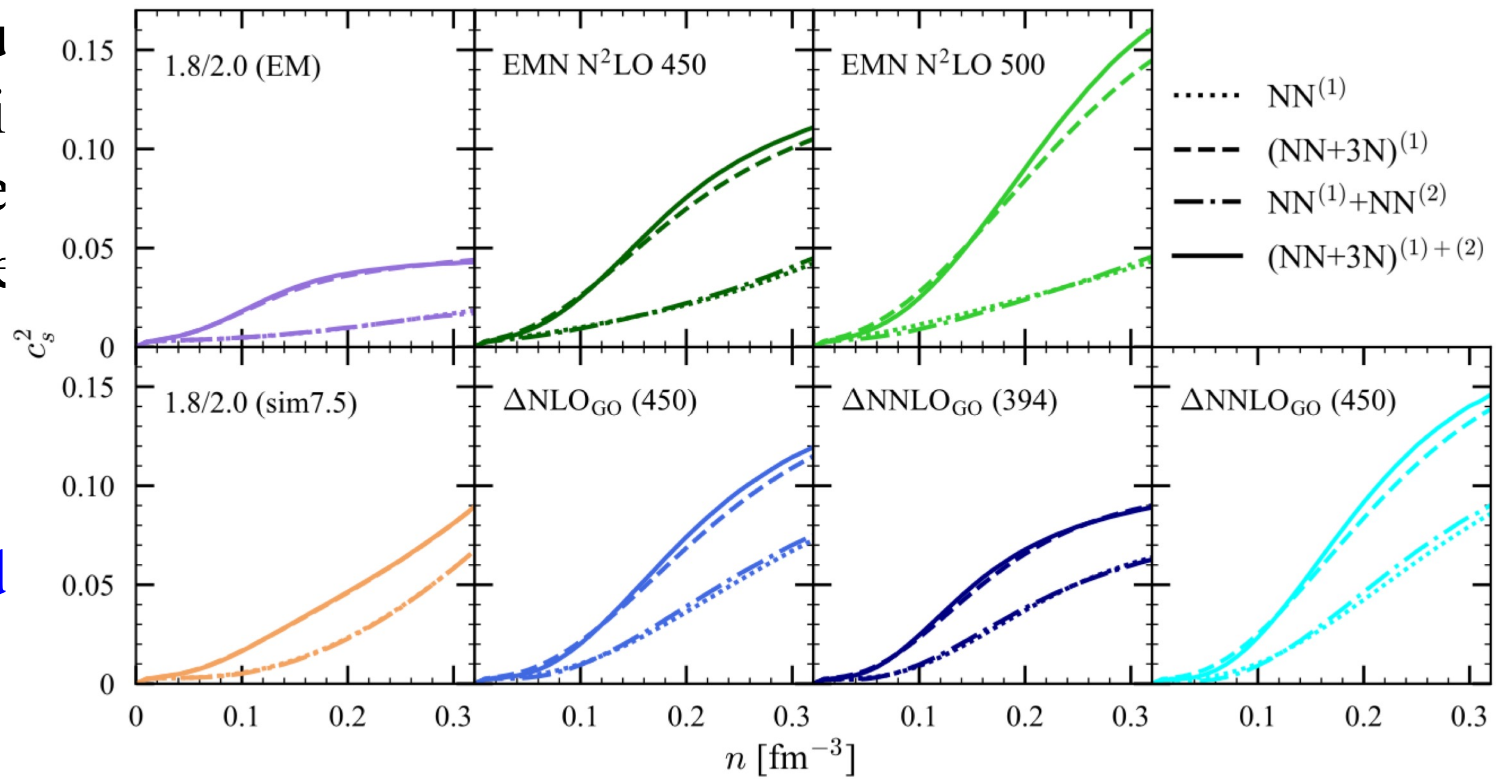


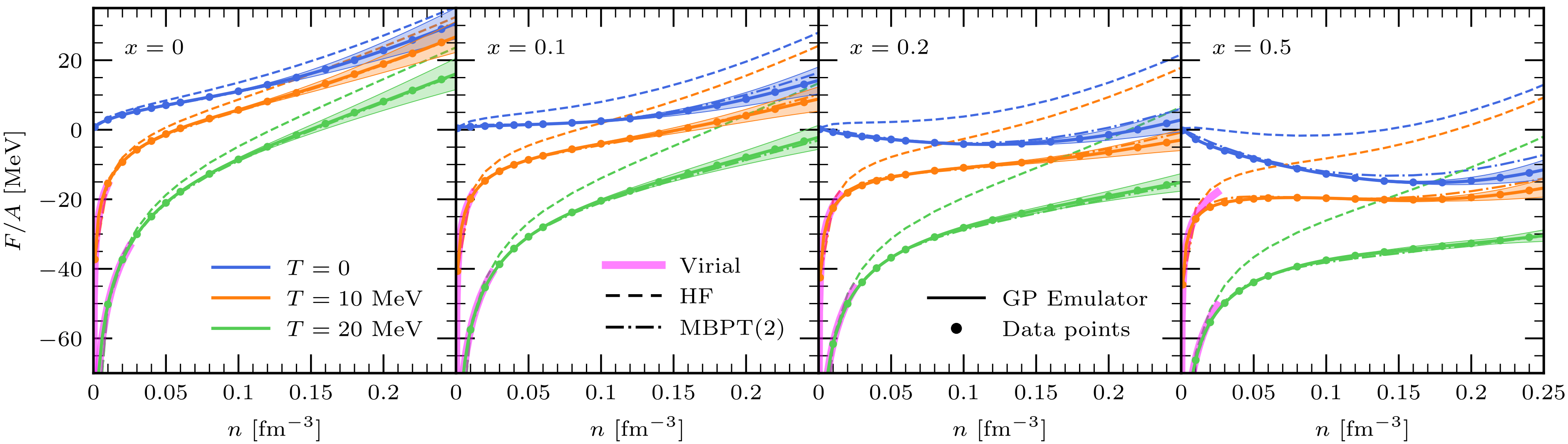
3N forces crucial for speed of sound

EOS for arbitrary proton fraction and temperature

Keller, Hebeler, AS, PRL (2023)

based on chiral NN+3N interactions to N^{3}LO

order-by-order EFT uncertainties + (smaller) many-body uncertainties



excellent reproduction of free energy data by Gaussian process (GP)

agrees with model-indep. virial EOS Horowitz, AS, NPA (2006) at low densities

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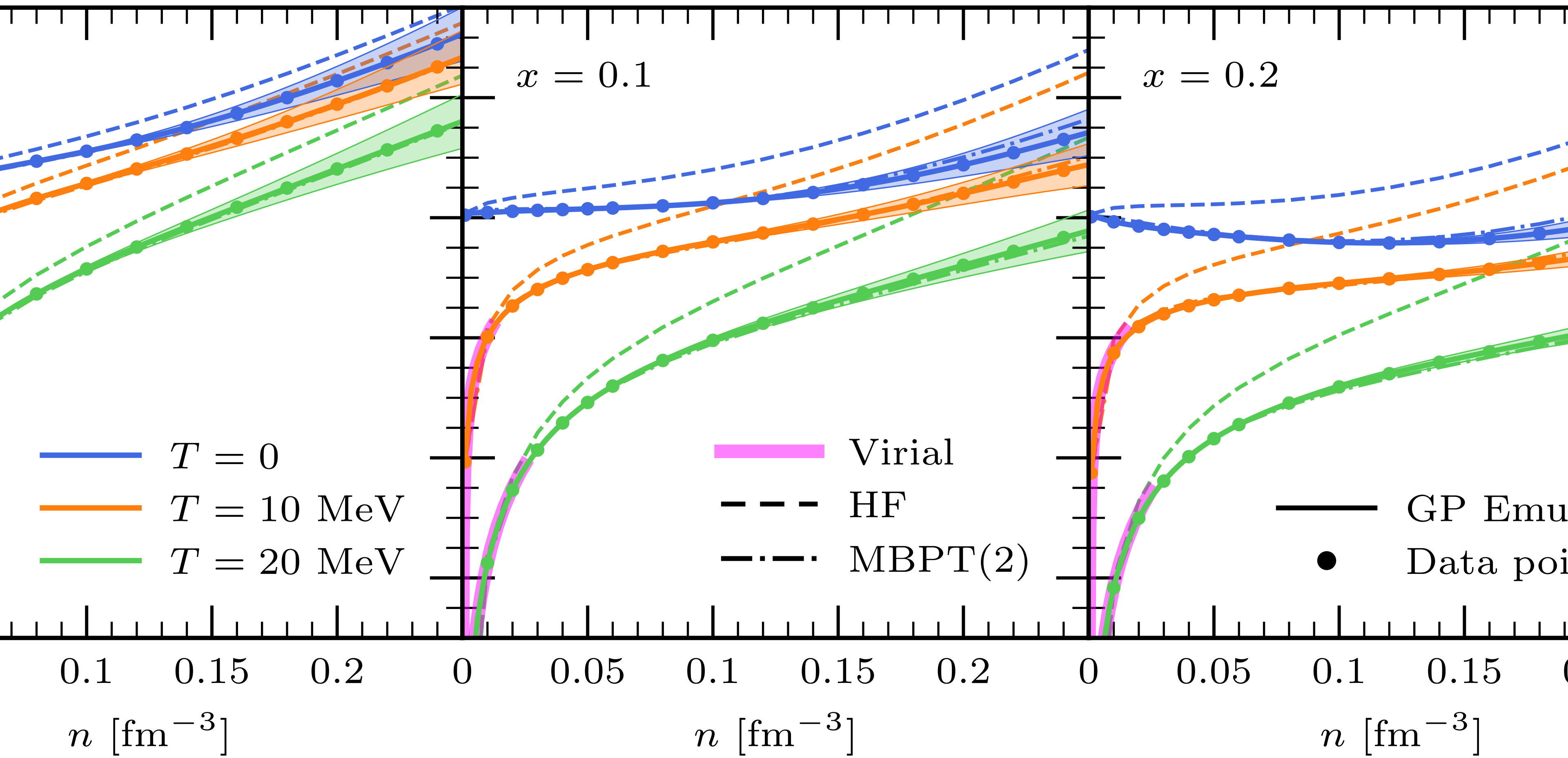

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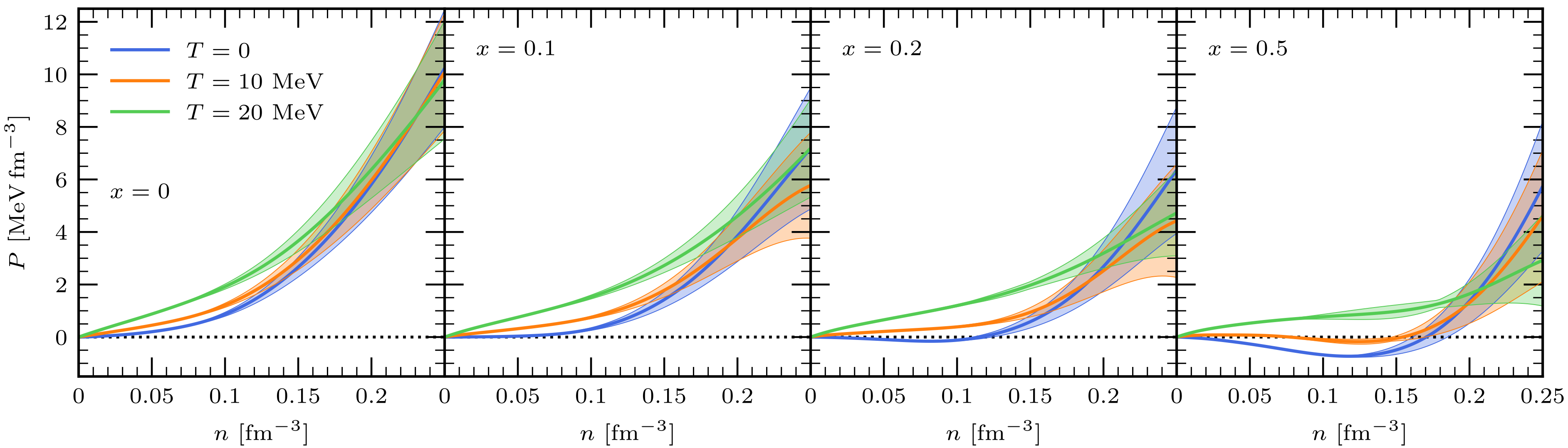
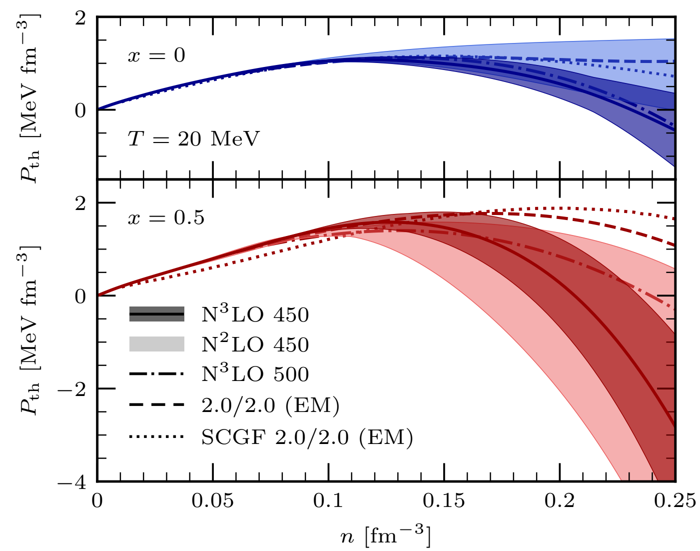
GP emulator to calculate pressure (thermodyn. consistent derivatives)



pressure isothermals cross at higher densities
→ negative thermal expansion

thermal part of pressure decreases with increasing density,
found for all chiral interactions studied,
is related to density dep. of m* from 3N



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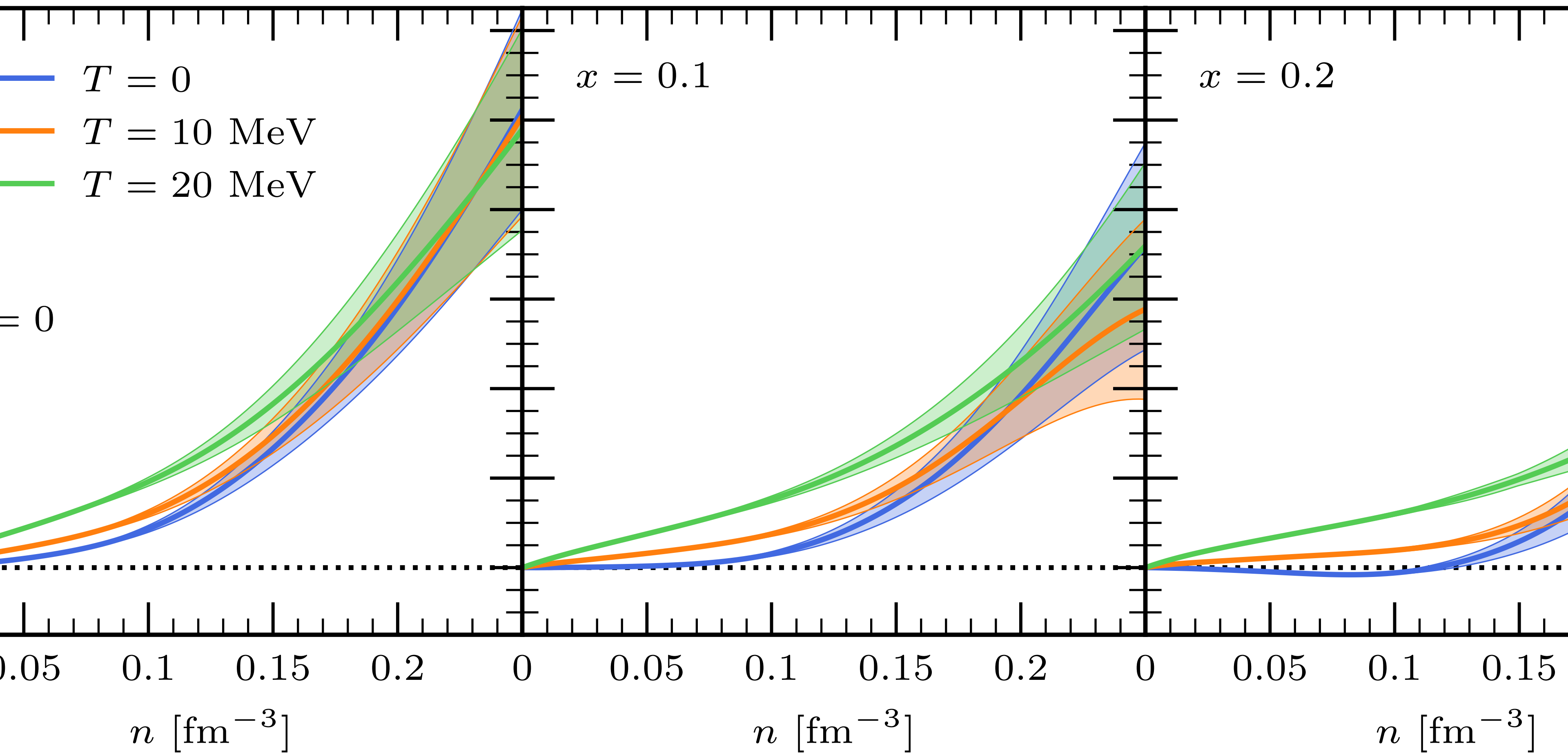

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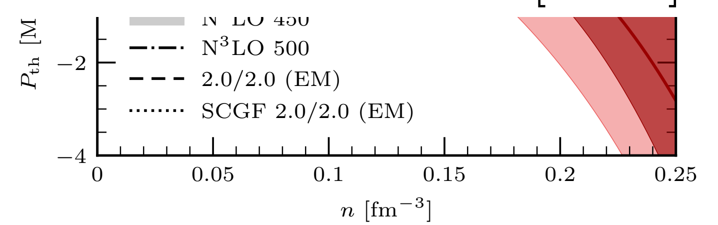
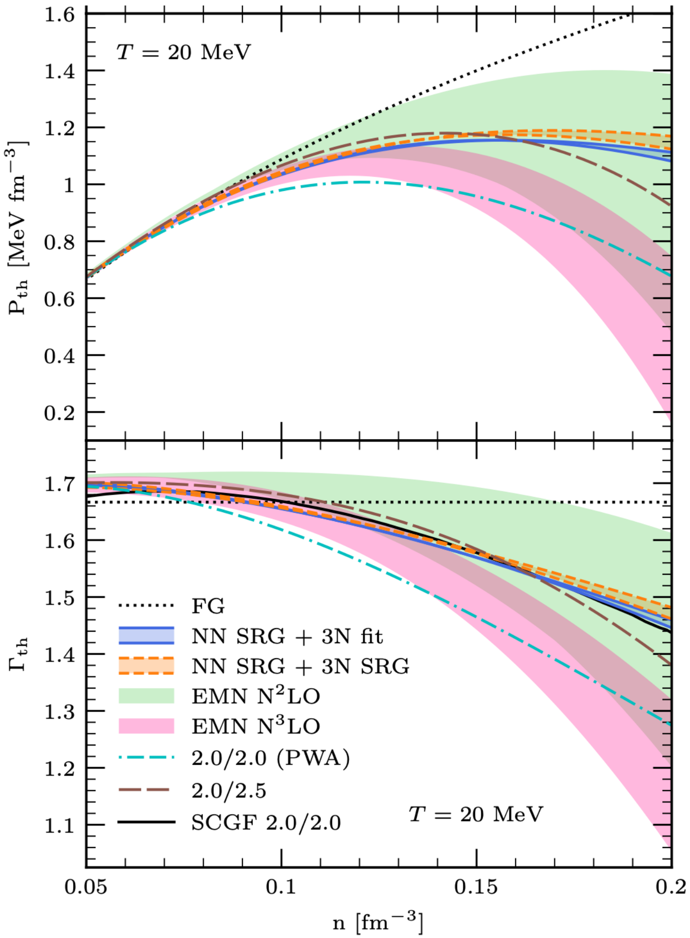


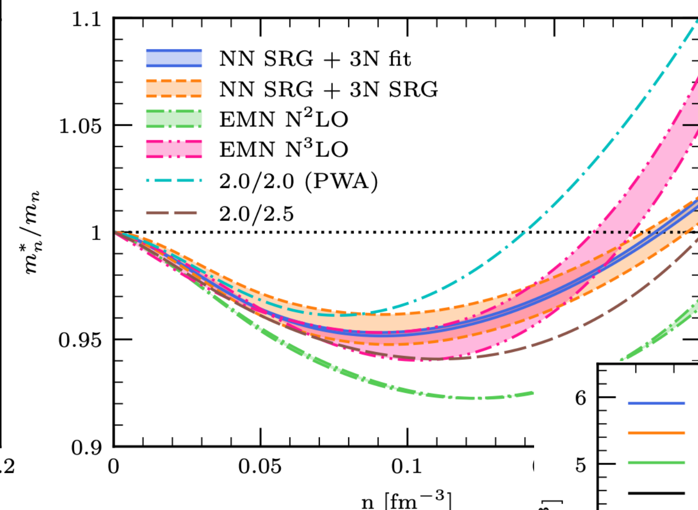
Thermal effects governed by effective mass

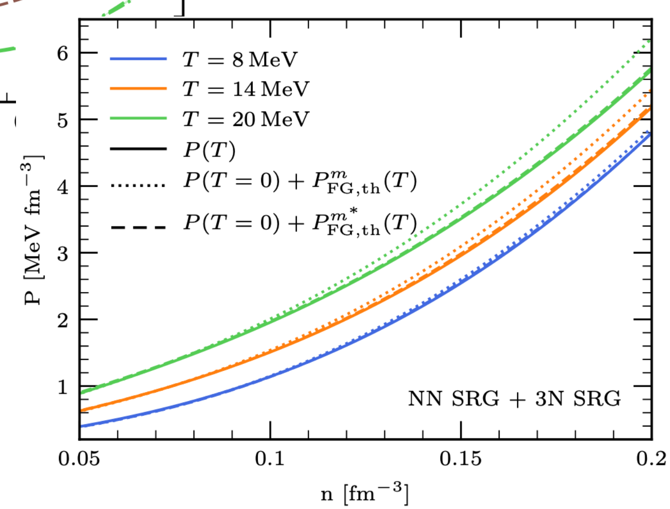


decreasing thermal pressure due to repulsive 3N contributions

increasing effective mass m^* beyond n_{sat}

$$\Gamma^*_{\rm th}(n) = \frac{5}{3} - \frac{n}{m^*_n}\frac{\partial m^*_n}{\partial n}$$





$$\Gamma_{\rm th}(T,n) = 1 + \frac{P_{\rm th}(T,n)}{\mathcal{E}_{\rm th}(T,n)}$$

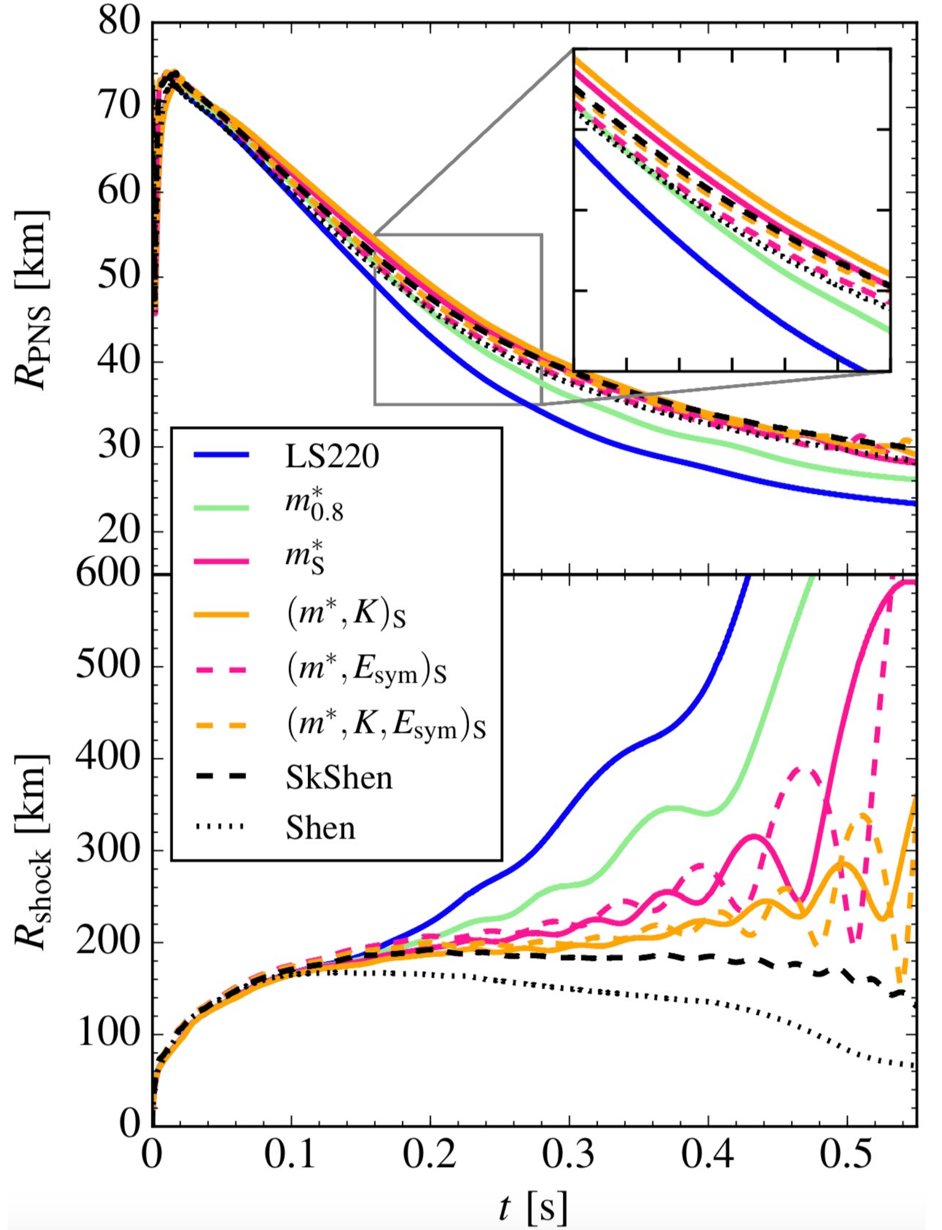
Keller, Wellenhofer, Hebeler, AS, PRC (2021)

Impact on core-collapse supernova simulations

Yasin, Schäfer, Arcones, AS, PRL (2019)

constructed EOS that systematically vary nuclear matter properties between LS and Shen et al. EOS

	m^*/m	K	$E_{\rm sym}$	L	n_0	B
LS220	1.0	220	29.6	73.7	0.155	16.0
Shen	0.634	281	36.9[a]	110.8	0.145	16.3
Theo.	0.9(2)	215(40)	32(4)	51(19)	0.164(7)	15.86(57)



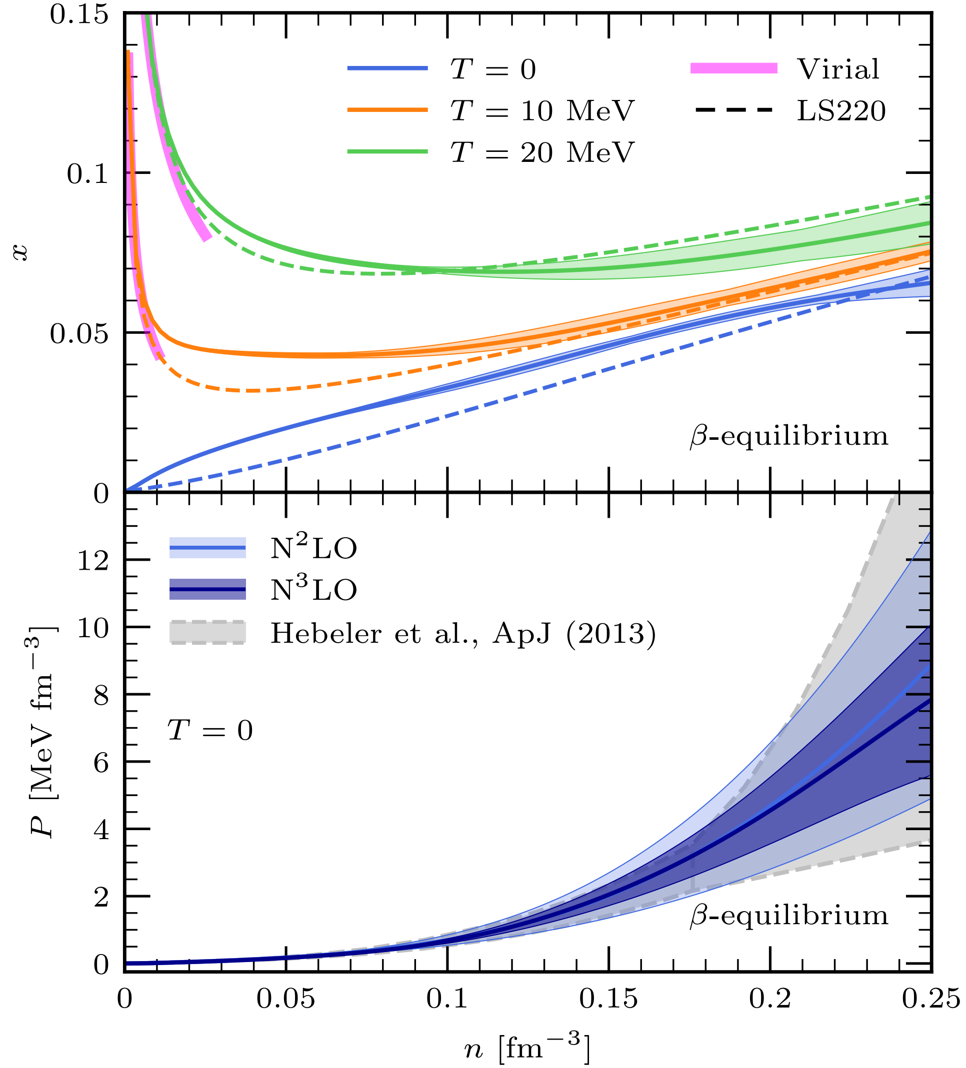
thermal contributions/m* are key for proto-neutron star contraction

faster contraction aids supernova shock to more successful explosion

EOS for neutron star matter in beta equilibrium

Keller, Hebeler, AS, PRL (2023)

use GP emulator to access arbitrary proton fraction,
solve for beta equilibrium



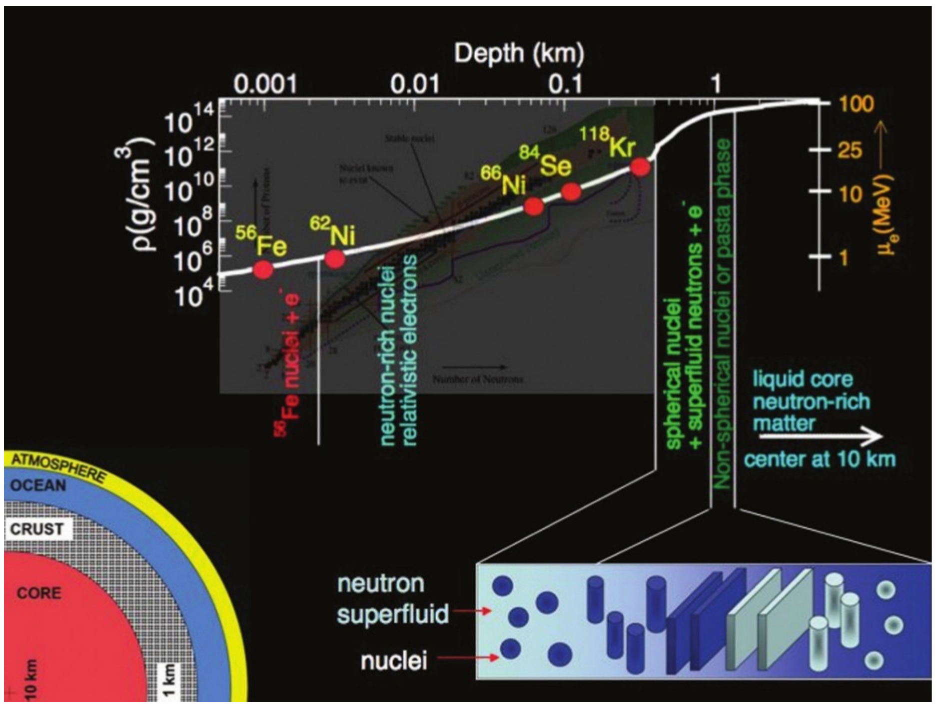
EOS of neutron star matter at N^2LO and N^3LO,
no indication of EFT breakdown

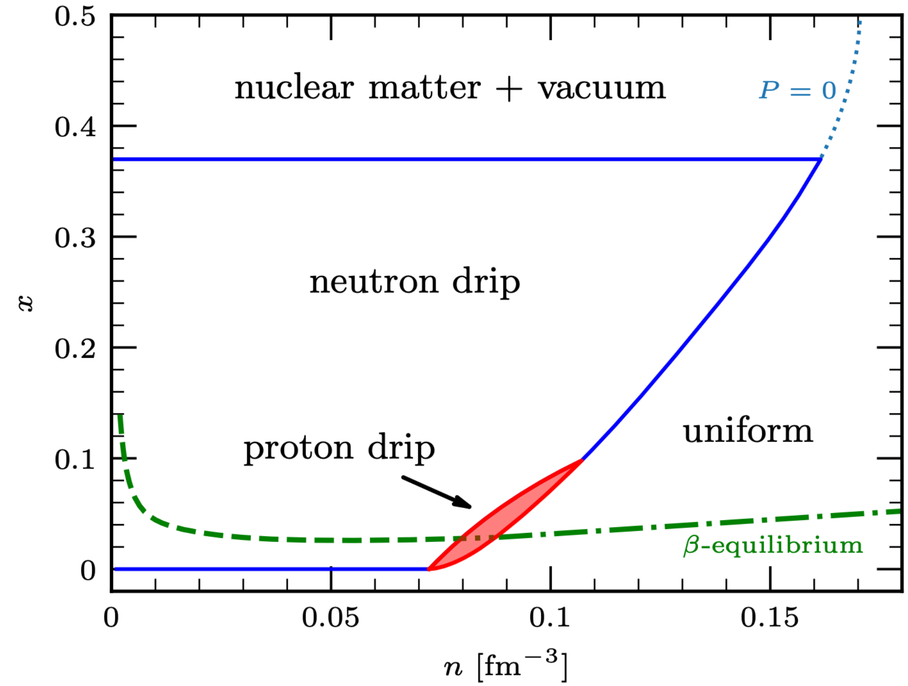
N^3LO band prefers higher pressures, improvement over older calculations

Subnuclear phase diagram of neutron star matter

~ 5% proton fraction in denser neutron matter

below ~ 0.5 n_0 possible pasta phases: clusters/structures of high density surrounded by neutron (and proton?) gas: neutron (and proton?) drip





Keller, Hebeler, Pethick, AS, PRL (2024)

Chiral EFT calculations establish proton drip:

robust for any reasonable EOS, proton drip aids pasta formation

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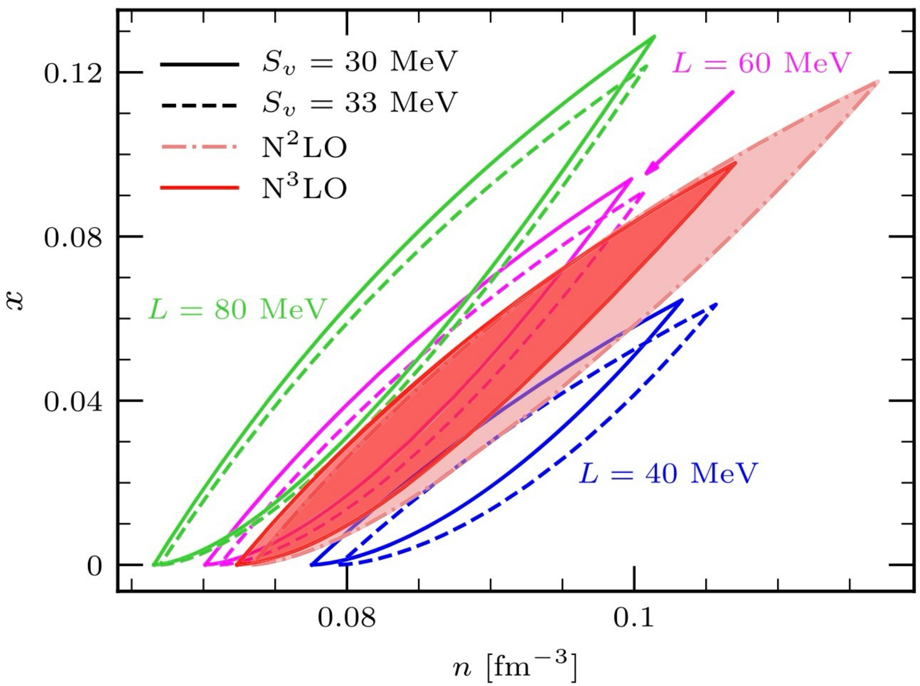

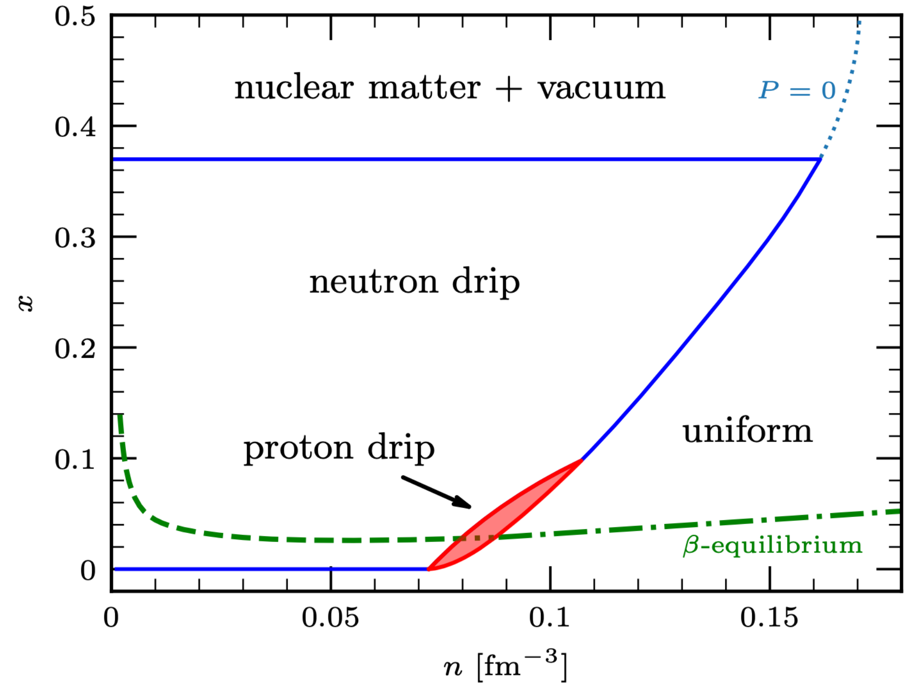

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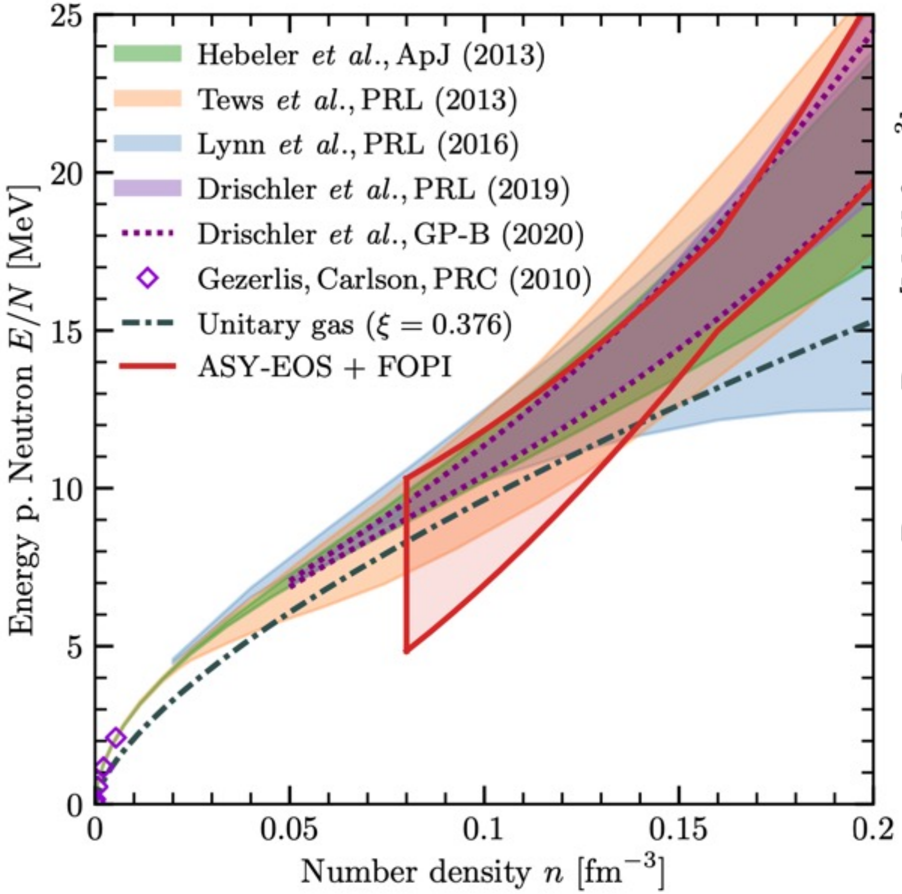
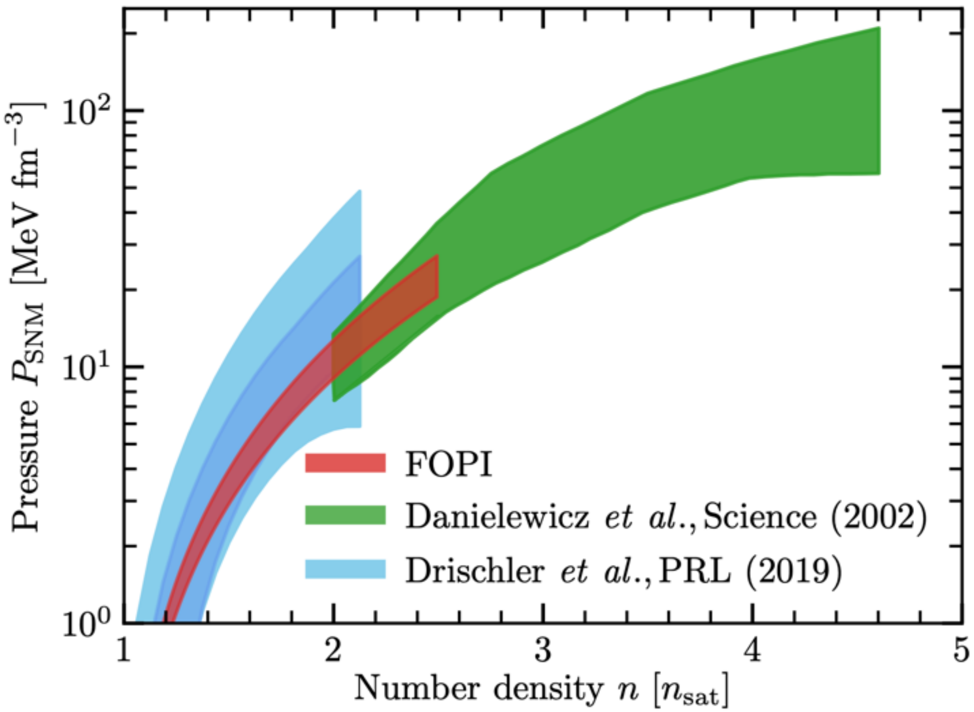
Constraints from heavy-ion collisions Huth, Pang et al., Nature (2022)

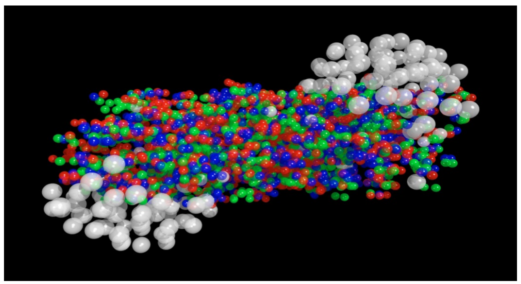
include in addition to chiral EFT: constraints from ASY-EOS and FOPI for neutron and symmetric matter

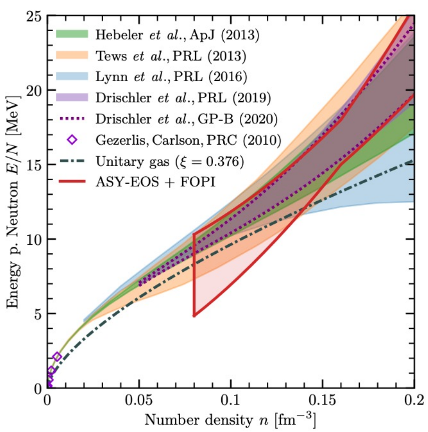


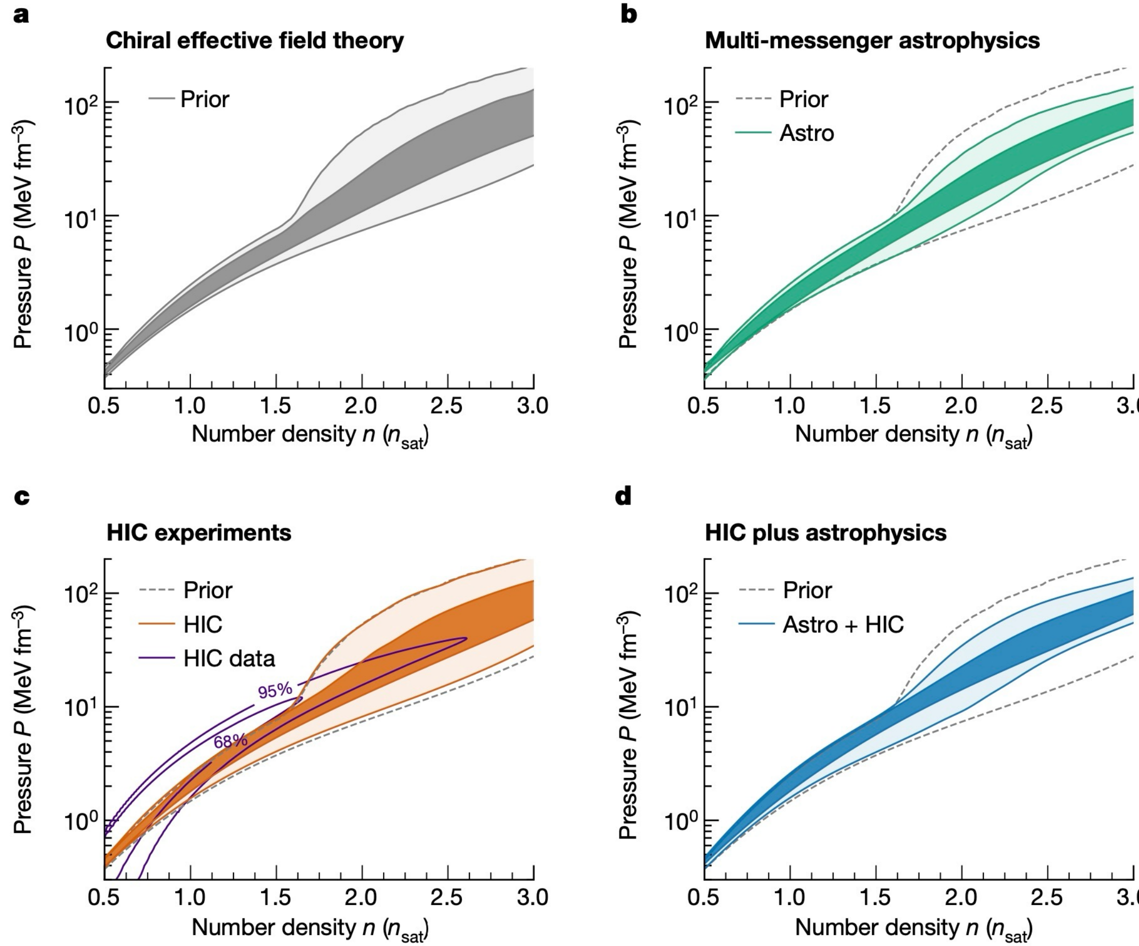


Constraints from heavy-ion collisions Huth, Pang et al., Nature (2022)

inclusion of HIC constraints prefers higher pressures, similar to NICER, overall remarkable consistency with chiral EFT and astro constraints







future HIC constraints for intermediate densities very interesting

	Prior	Astro only	HIC only	Astro + HIC
$P_{1.5n_{\rm sat}}$	$5.59^{+2.04}_{-1.97}$	$5.84^{+1.95}_{-2.26}$	$6.06^{+1.85}_{-2.04}$	$6.25^{+1.90}_{-2.26}$
$R_{1.4}$	$11.96^{+1.18}_{-1.15}$	$11.93^{+0.80}_{-0.75}$	$12.06^{+1.13}_{-1.18}$	$12.01^{+0.78}_{-0.77}$

Summary

Thanks to:
ab initio masses for r-process: **J. Kuske, T. Miyagi**, A. Arcones
EOS: **F. Alp, Y. Dietz, H. Göttling, L. Hoff, J. Keller, M. Mendes, I. Svensson**, K. Hebeler, J.M. Lattimer, C.J. Pethick

ab initio calculations based on chiral EFT interactions for nuclei and dense matter: cold, finite temperature, arbitrary proton fraction, density dependence of effective mass leads to decreasing P_{th}

reliable EOS up to ~ 1-2 n_0 with controlled EFT and many-body uncertainties: key for multimessenger era of neutron stars,

high-density constraints from astrophysics see Melissa's talk
+ heavy-ion collisions need better uncertainty quantification for HICs